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FROM (d,p) REACTIONS AT 21 MEV

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SUMMARY

The proton polarization in deuteron stripping has been measured for the target nuclei beryllium (Be^9), boron (B^{10}), carbon (C^{12}), silicon (Si^{28}), and calcium (Ca^{40}) between 20° and 120° . The results are generally consistent with other polarization measurements at 13.6 and 15.0 Mev, but they differ markedly from polarization data at lower deuteron energies. A comparison of ground and first excited-state polarizations in Be^9 suggests that the total angular momentum j_n for the captured neutron in both states is the same, that is, $j_n = 3/2$. For the C^{12} reaction, a comparison of the proton polarization with the cross section asymmetry, induced by 22-Mev vector-polarized deuterons, shows a linear relation that is compared with the Distorted Wave Born Approximation (DWBA) predictions. The differential cross sections for deuteron stripping from Be^9 , C^{12} , and Ca^{40} have also been measured.

INTRODUCTION

Since the first theoretical interpretation by Butler, (d,p) stripping reactions have been very useful in nuclear spectroscopy for determining spin, parity and width of nuclear levels. Later the development of the Distorted Wave Born Approximation (DWBA) made it possible to fit both the shape and the absolute value of the differential cross section (refs. 1 to 3).

Fitting polarization data is a more stringent test of the theory because the polarization of the outgoing protons depends critically on the distortion of the incoming and outgoing waves produced by the optical potentials, particularly when spin-dependent interactions are important. The polarization is apparently very sensitive to interference between the stripping reaction and other processes such as compound nucleus formation (ref. 4).

If the distorting potential is purely central, the predictions of the DWBA for polarization are (refs. 5 and 6)

$$\left. \begin{array}{l} \text{or} \\ P \leq \frac{1}{3} \quad \text{for} \quad j_n = l_n - \frac{1}{2} \\ P \leq \frac{1}{3} \frac{l}{l+1} \quad \text{for} \quad j_n = l_n + \frac{1}{2} \end{array} \right\} \quad (1)$$

$$P_{l_n=0} = 0 \quad (2)$$

$$A = 3P_p P_d \quad (3)$$

where P is the magnitude of the polarization, j_n is the total angular momentum, l_n is the orbital angular momentum of the captured neutron, A is the right-left asymmetry in the differential cross section when polarized deuterons are stripped, P_p is the proton polarization for stripping with unpolarized deuterons, and P_d stands for the component of the deuteron vector polarization perpendicular to the reaction plane (parallel to P_p).

On the other hand, if spin-dependent distortions of the deuteron and/or the proton are included in the DWBA, complete polarization is possible, the null restriction for $l_n = 0$ reactions is removed, and the relation between A and P_p is no longer as simple as it is in equation (3).

The sign of the polarization can be predicted by a semiclassical model first given by Newns (ref. 7). If the deuteron absorption outweighs the proton absorption, it should be found that $P \gtrless 0$ for $j_n = l_n \pm 1/2$; and if the proton distortion is dominant, the sign of P is the converse.

When polarization experiments in (d,p) reactions were planned, only a small amount of data existed. In order to provide more detailed experimental information, the proton polarization was measured over a wide angular range for several values of l_n and j_n . In addition, the Saclay group was prepared to study elastic deuteron scattering and deuteron stripping reactions with 22-Mev vector-polarized deuterons. Their results together with the (d,p) polarization and cross section data from Lewis could present a set of data for studying spin-dependent interactions in deuteron stripping.

SYMBOLS

A right-left asymmetry in differential cross section when polarized deuterons are stripped

A_s instrumental asymmetry

$\frac{dE}{dX}$ differential energy loss

E energy

E_d	deuteron energy
j_n	total angular momentum of captured neutron
K_d	wave number of deuteron
K_p	wave number of proton
k_{in}	wave number of incident particle
k_{out}	wave number of outgoing particle
l_n	orbital angular momentum of captured neutron
$\langle m \rangle$	expectation value of orbital angular momentum along quantization axis
\vec{n}	axis of quantization
P	polarization
P_c	known proton polarization for carbon
P_d	component of deuteron vector polarization perpendicular to reaction plane (parallel to P_p)
P_p	proton polarization for stripping with unpolarized deuterons
P_{st}	proton polarization in deuteron stripping
Q	reaction energy
R, L	number of protons scattered to right and left, respectively
δ	mixing ratio
σ_1, σ_2	differential cross sections of first and second scattering, respectively
$\sigma(\theta)_{pol}, \sigma(\theta)_{unpol}$	differential cross sections measured with polarized and unpolarized deuterons, respectively
Ω	solid angle
Subscripts:	
CM	center of mass frame
fes	first excited state

gs ground state

lab laboratory mass frame

EXPERIMENTAL PROCEDURE

Apparatus

The proton polarization P_{st} was determined by the double-scattering technique with the elastic scattering from carbon at 45° as an analyzer. The value of P_{st} was found from the measured right-left asymmetry by means of the relation

$$\frac{R - L}{R + L} = P_{st} P_c \quad (4)$$

where R and L are the number of protons scattered to the right and left, respectively, and P_c is the known polarization for carbon. The positive axis is taken along $\vec{n} = \vec{k}_{in} \times \vec{k}_{out}$ in accord with the Basel Convention.

Figure 1 shows the experimental setup. It consists of a scattering chamber where the deuteron stripping takes place and a polarization analyzer where the reaction protons are scattered to the right and left. A deuteron beam, collimated to about 1/8 by 3/8 inch, was used to bombard targets of the following thicknesses (mg/sq cm): beryllium (Be), 37; boron (B^{10}) (96 percent enriched), 25; carbon (C), 23; silicon (Si) (natural mixture), 20; and calcium (Ca) (natural mixture), 30. The beam current averaged 1.5 microamperes, while its energy at the target center was approximately 20.7 ± 0.3 Mev. The polarimeter had an angular acceptance of 2.5° ; 70-milligrams-per-square-centimeter carbon was used for an analyzing target. The double-scattered protons were detected by cesium iodide CsI (Tl) counter telescopes. Pulses from the right and left E counter were amplified and routed directly into the subgroups of a 200 channel pulse-height analyzer. The only pulses stored, however, were those in coincidence with pulses from the dE/dX counters which exceeded a certain bias level. The background counts from the E detector, due to the high neutron and gamma flux, were reduced in the analyzer to a negligible amount by this coincidence requirement. Where necessary, the background was determined by making a run

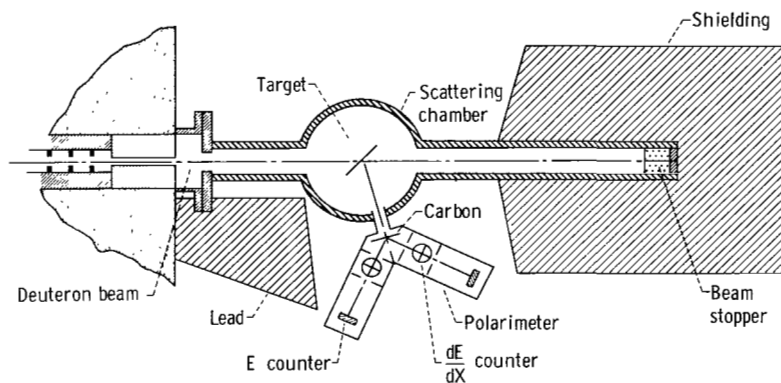


Figure 1. - Schematic of experimental setup.

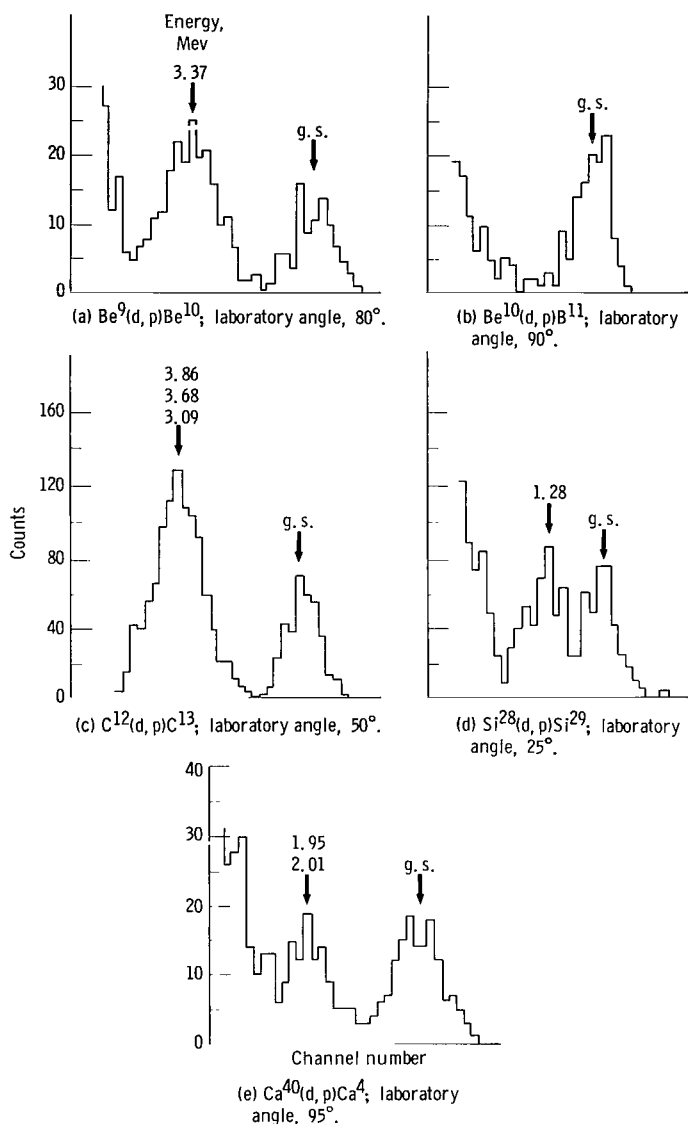


Figure 2. - Typical pulse-height spectra produced by polarimeter.

with a lead absorber inserted between first and second scattering. The (d,p) reactions in the polarimeter target were eliminated by degrading the elastically scattered deuterons with beryllium foils between the first and second scattering. Typical pulse-height spectra displayed in the multichannel analyzer are shown in figure 2. Generally, no difficulties were encountered in separating the elastic from the inelastic peak. The separation error was equal to or smaller than the statistical error and has been included in the total error. A 4-percent energy resolution was required to separate ground and first excited state in Si^{29} . In order to obtain this resolution, the angular acceptance of the counters after the second scattering was changed from 8° to 4° , the analyzer target thickness was reduced to 20 milligrams per square centimeter (400 Kev), and the reaction protons were degraded in energy by 30 percent.

Instrumental Asymmetries

The following is a list of the possible asymmetries and the corrective measures taken.

Misalignment of axis of polarimeter with center of stripping target. - As a preventive measure, all the mechanical parts were machined to close tolerances, the shifts of the incident deuteron beam on the target were restricted so as to produce no more than a 2 percent asymmetry. As a check, the polarization was measured at several angles with the polarimeter at positive and negative stripping angles.

Asymmetries due to electronic shifts and inherent asymmetries within polarimeter. - As a check of long-term electronic drifts during the extended runs, the polarimeter was periodically moved into the direct beam, and protons from (d,p) reactions in the analyzing target were used to test the routing

and coincidence electronics. Usually no adjustments during the runs were necessary.

Short-term gain fluctuations and asymmetries within the polarimeter were compensated for by frequent inversions with respect to the asymmetry axis during the course of the run. In the up position, subgroups 1 and 2 of the pulse-height analyzer received the spectra of the right and left counters; in the down position, the same information was stored in subgroups 3 and 4. Thus, any gain shifts were easily discernible and in general were found to be negligible. This fact made it possible to determine the asymmetries in the silicon reaction where the proton groups were not clearly separated by counting equal "bands" of channels in corresponding spectra.

Asymmetries due to finite extension of second target. - The instrumental asymmetry due to the extended second target was corrected using the expression of Evans (ref. 8) neglecting second-order terms. The final expression for this asymmetry was

$$A_s = -4.2 \times 10^{-4} \frac{\sigma'_1}{\sigma_1} \left(\frac{\sigma'_2}{\sigma_2} - 1.45 \right) \quad (5)$$

where σ_1 and σ_2 are the differential cross sections in the first and second scattering, respectively, and σ'_1 and σ'_2 are the corresponding derivatives with respect to angle. This correction is applied as follows:

$$P_{st} P_c = \frac{R - L}{R + L} - A_s \quad (6)$$

The values of σ_2 and σ'_2 were taken from Peelle (ref. 9); σ_1 and σ'_1 were obtained from Zeidman et al. (ref. 10) for boron and from the present study for beryllium, carbon, silicon, and calcium. Generally, A_s was less than 1 percent, but for a few angles it increased to 2.5 percent.

Analyzing Power

To obtain the (d,p) polarization from the corrected right-left asymmetry,

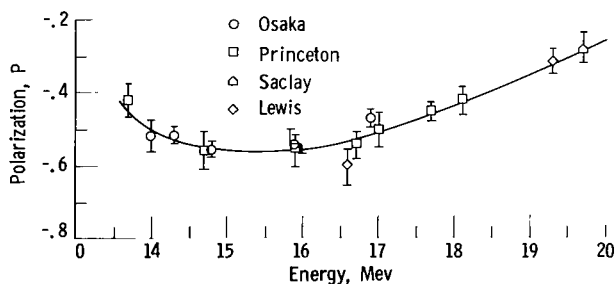


Figure 3. - Polarization of protons elastically scattered from carbon. Laboratory angle, 45°.

the analyzing power of the polarimeter must be known over the energy range of the reaction protons analyzed. Figure 3 shows the existing data for the elastic proton polarization from carbon at 45° (laboratory angle) for incident proton energies between 13.5 and 20.0 Mev (refs. 11 to 14). In order to operate the polarimeter in the region of largest polarization, the protons were degraded to the range of 15 to 17.5 Mev by beryllium absorbers.

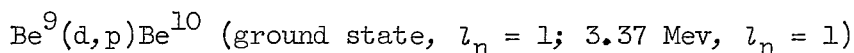
EXPERIMENTAL RESULTS

The experimental results of this polarization study are presented in table I. The errors in the polarization data contain the statistical errors, separation errors, estimates of the instrumental asymmetries, and errors in the carbon elastic proton polarization. The relative differential cross section data obtained at Lewis for deuteron stripping from beryllium, carbon, and calcium and the results from Zeidman, et al. (ref. 10) for boron are also listed in this table.

TABLE I. - EXPERIMENTAL DATA

Laboratory angle, Θ_{lab} , deg	Center of mass angle, Θ_{CM} , deg	Polarization, $P \pm \delta P$	Differential cross section, $\frac{d\sigma}{d\Omega}$, arbitrary units	Laboratory angle, Θ_{lab} , deg	Center of mass angle, Θ_{CM} , deg	Polarization, $P \pm \delta P$	Differential cross section, $\frac{d\sigma}{d\Omega}$, arbitrary units
Be ⁹ (d,p)Be ¹⁰ ground state				C ¹² (d,p)C ¹³ ground state			
21	23.2	0.077±0.077	9.0	21	23.2	0.107±0.097	73.2
30	33.3	.091±.170	4.0	30	33.5	.137±.075	19.8
40	45.0	.039±.105	2.4	35	39.0	-.252±.070	15.6
45	50.4	-.002±.060	2.2	40	44.0	-.552±.085	15.4
50	55.9	-.200±.050	1.8	45	49.3	-.535±.085	15.6
55	61.3	-.120±.023	1.25				
60	66.6	-.138±.040	.95	50	54.7	-.440±.075	13.9
65	72.0	-.036±.072	.78	55	60.0	-.122±.069	11.3
70	77.3	-.031±.140	.75	60	65.4	.006±.027	8.2
80	87.6	.054±.065	.77	65	70.8	.407±.061	6.4
90	97.7	.043±.060	.75	70	76.0	.332±.053	4.9
105	112.5	.075±.075	.43				
Be ⁹ (d,p)Be ¹⁰ (3.37 MeV)				75	81.0	.085±.075	4.7
21	23.8	0.100±0.082	9.5	80	86.1	.065±.044	4.5
30	33.9	.004±.096	3.7	85	91.1	-.192±.073	3.9
40	45.0	-.160±.036	2.4	90	96.1	-.161±.037	3.4
45	50.4	-.130±.038	2.1	95	101.2	-.205±.057	2.8
50	55.9	-.146±.025	1.7	100	106.0	-.178±.080	2.4
55	61.3	-.089±.045	1.3	Si ²⁸ (d,p)Si ²⁹ ground state			
60	66.6	-.032±.040	.90	21	22.0	0.144±0.135	---
65	72.0	.021±.073	.80	25	26.1	-.085±.109	---
70	77.3	-.007±.091	.74	30	31.3	-.021±.056	---
80	87.6	-.050±.065	.76	35	36.4	-.025±.081	---
90	97.7	-.070±.098	.68	40	41.6	-.040±.161	---
B ¹⁰ (d,p)B ¹¹ ground state				60	62.2	.119±.120	---
21	23.2	0.145±0.059	48.0	Ca ⁴⁰ (d,p)Ca ⁴¹ ground state			
25	27.9	.148±.046	31.0	21	21.6	0.042±0.046	5.3
30	33.2	.131±.040	17.0	30	30.9	.125±.034	4.5
35	38.6	.088±.076	12.7	35	36.0	.143±.025	2.6
40	44.0	.057±.060	11.2	40	41.2	.145±.026	1.75
45	49.5	-.034±.034	11.8	45	46.3	-.010±.031	1.00
50	54.7	.092±.068	10.7	50	51.4	-.105±.037	.91
55	60.2	.070±.062	8.4	55	56.5	-.102±.033	1.00
60	65.5	.166±.058	6.5	60	61.6	-.012±.046	.91
65	71.0	.156±.051	5.1	65	66.7	-.006±.052	.75
70	76.0	.204±.039	4.9	70	71.7	-.036±.066	.66
75	81.2	.133±.068	5.0	75	76.7	-.079±.047	.55
80	86.2	.046±.083	5.2	80	81.8	-.194±.081	.51
85	91.3	.032±.058	4.3				
90	96.3	.080±.098	4.7	85	86.8	-.224±.042	.45
95	101.4	.139±.082	4.0	90	91.8	-.140±.055	.38
100	106.2	.204±.096	3.6	95	96.9	-.011±.060	.30
105	111.0	.134±.081	3.1	105	106.8	+.036±.065	.25
110	116.0	.088±.078	2.7	115	116.7	-.050±.080	.27

DISCUSSION



A comparison of the Lewis results for the $\text{Be}^9(d,p)\text{Be}^{10}$ (ground state) reaction at 20.6 Mev with data between 7.8 and 15.0 Mev (refs. 15 to 19) is shown in figure 4. All the data points in the energy range from 7.8 to 13.6 Mev have the same trend, as indicated by the dashed curve. Between 13.6 and 15.0 Mev, a drastic change occurs that might be due to interference from compound nuclear states. At 15.0 Mev, the polarization is close to zero for angles less than 30° and is negative beyond. At 20.6 Mev, the shape of the distribution is very similar to the one at 15.0 Mev, but the curve is shifted to larger angles. For all energies, the polarization is positive at the stripping peak in agreement with Newns' "sign rule" for predominant deuteron distortion.

In figure 5, the ground state (g.s.) polarization at 15.0 and 20.6 Mev are replotted along with the corresponding first excited-state (f.e.s.) polarizations. The 20.6-Mev stripping cross sections for both levels are shown at the bottom of the figure. There are three interesting features. First, the shapes of all polarization distributions are very similar. Secondly, the curves are shifted to smaller angles as the kinetic energy of the outgoing protons decreases. Thirdly, the differential cross section for g.s. and f.e.s are nearly identical at the deuteron bombarding energy of 20.6 Mev.

Although theoretical calculations in this energy region still have to be done, the data of figure 5 might suggest the following:

(1) The angular shift in the polarization distribution is largely due to the effects in the exit channel.

(2) The excitation of the 3.37-Mev state in Be^{10} will proceed preferably through the $j_n = 3/2$ channel.

In support of the first suggestion, the deuteron stripping reaction may be considered as a three-stage process; that is, the deuteron is scattered by the target, the deuteron is stripped, and the proton is scattered by the residual nucleus. The first stage of this process will be the same when comparing the ground and first excited states at a particular deuteron energy. The second stage will also be very similar if the proton-neutron inter-

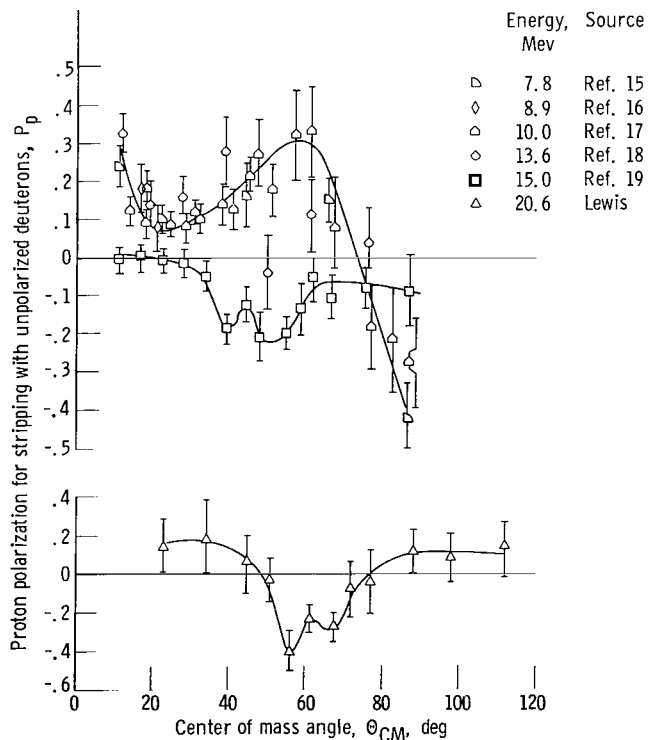


Figure 4. - Proton polarization from $\text{Be}^9(d,p)\text{Be}^{10}$ ground state reaction.

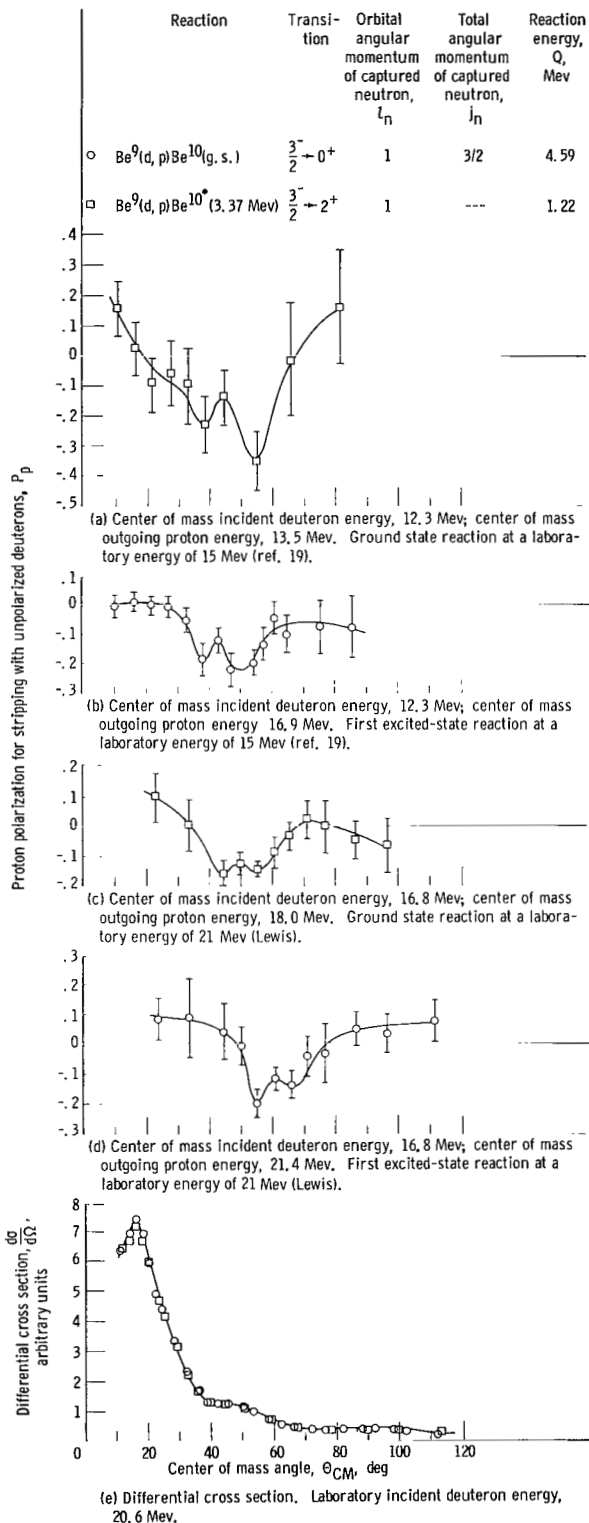


Figure 5. - Proton polarization and differential cross section from $\text{Be}^9(d, p)\text{Be}^{10}$ reaction.

action and the orbital angular momentum of the captured neutron is the same. Therefore, in reactions that satisfy these conditions, differences between the g.s. and f.e.s. polarizations might be attributed to effects in the exit channel. This indeed seems to be the case for beryllium; comparing the curves in figures 5(c) and (d), both having center of mass incident deuteron energy of 16.8 Mev. Also, it may be seen that the g.s. and f.e.s. cross sections are identical, which supports the contention that the stripping stage of the process is the same. Finally, the curves in figures 5(b) and (c) are compared where the outgoing proton energies are fairly close (1 Mev different) but the incident deuteron energies are 4.5 Mev apart. These two curves show less shift than the curves in figures 5(c) and (d).

The nature of these effects in the proton channel can only be speculated. Compound nuclear interference seems to be unimportant in this energy region, because of the smooth variation of cross section and polarization with energy. If this is correct, other changes in the distorting potential, possibly its spin-dependent part, could be responsible for the shift of the polarization curves. The existence of spin-dependent interactions is supported by the fact that the polarization in $\text{Be}^9(d, p)\text{Be}^{10}$ is larger than the predictions of the central potential DWBA.

Since the total angular momentum of the neutron captured in the 3.37-Mev state in Be^{10} is still not known unambiguously, we will try to obtain it from the present polarization result. In cases where the spin-orbit forces are considered negligible, Huby et al. (ref. 5) have shown that if the neutron is captured in a definite state of orbital angular

momentum, the polarization of the outgoing proton is

$$P_l(K_d, K_p) = \frac{1}{3} \left(\frac{\Theta_{l+\frac{1}{2}}^2}{l+1} - \frac{\Theta_{l-\frac{1}{2}}^2}{l} \right) \frac{\langle m \rangle}{\Theta_{l+\frac{1}{2}}^2 \Theta_{l-\frac{1}{2}}^2} \quad (7)$$

where $\Theta_{j=l \pm \frac{1}{2}}^2$ are the reduced widths for the neutron being captured in states of total angular momentum $j = l \pm \frac{1}{2}$ and $\langle m \rangle$ is the expectation value of the orbital angular momentum along the quantization axis. If it is assumed that the expectation values will be roughly the same for the g.s. and the f.e.s. reactions, the ratio of the f.e.s. polarization to the g.s. polarization will be a constant (independent of angle)

$$\frac{P_{fes}}{P_{gs}} = \frac{\delta^2 - 2}{\delta^2 + 1} \quad (8)$$

where $\delta = \frac{\Theta_{3/2}}{\Theta_{1/2}}$ is the mixing ratio for the first excited state. This means both polarization distributions must have similar shape and be in phase.

The data of this report do not rigorously support this consequence of the central potential theory. The shapes of the polarization distributions are indeed very similar; however, there appears to be a small phase factor. If it is assumed that this phase factor is due to an interaction that is not contained in the central potential DWBA (e.g., a spin-dependent force) and that is small enough to act only as a perturbation, then equation (8) can be used to find δ from the relative size of the polarization patterns by neglecting the angular shift. Since $\frac{P_{fes}}{P_{gs}} \approx 1$, it follows that the excitation of the 3.37-Mev state in Be^{10} will proceed like the ground state preferably through the $j_n = 3/2$ channel.

The (d,p) angular correlation measurements of Taylor (ref. 20) give two possible values for the mixing ratio, $\delta = -2.65$ and $\delta = -0.38$. The data contained in this report supports the first of these values, which would indicate $\frac{P_{fes}}{P_{gs}} = 0.63$. The errors of Taylor's values are between 10 and 15 percent.

Hird and Strzalkowski (ref. 21) have measured the cross section asymmetry from deuteron stripping with vector-polarized deuterons for the g.s. and f.e.s. reactions in Be^9 . Their data indicate $j_n = 1/2$ for the excited state. This conclusion was based on only two data points, however, and considerable tensor

contribution in the polarized deuteron beam could have been present.

$B^{10}(d,p)B^{11}$ (ground state, $l_n=1$)

In figure 6, the polarization data are plotted for 7.8, 8.9, 10.0, 11.4, 13.6, and 21.0 Mev (refs. 16, 18, and 22 to 24). The polarization changes drastically between 10 and 11.4 Mev. Another rapid change occurs between 11.4 and 13.6 Mev. The polarization curve at 13.6 and 21 Mev are identical within experimental uncertainties and seem to indicate a more consistent behavior at the higher energies. The rapid changes in the region of 11.4 Mev seem to be local fluctuations due to compound nuclear interferences. The magnitude of the polarization is larger than that predicted by the central potential DWBA. The sign rule, $P > 0$ for $j = l + 1/2$, is obeyed. The oscillations in the polarizations at 21 Mev are more rapid than those at 10 Mev; this is reflected in the differences in the differential cross sections (refs. 10 and 25).

$C^{12}(d,p)C^{13}$ (ground state, $l_n=1$)

This reaction has been studied experimentally at many energies. The data between 6 and 21 Mev (refs. 16, 22, and 26 to 31) are plotted in figure 7. Apart from the existence of some fine structure in the region of 50° (center of mass angle) at 10- and 15-Mev deuteron energy, the general trend of all the data up to 15 Mev is the same and can be represented

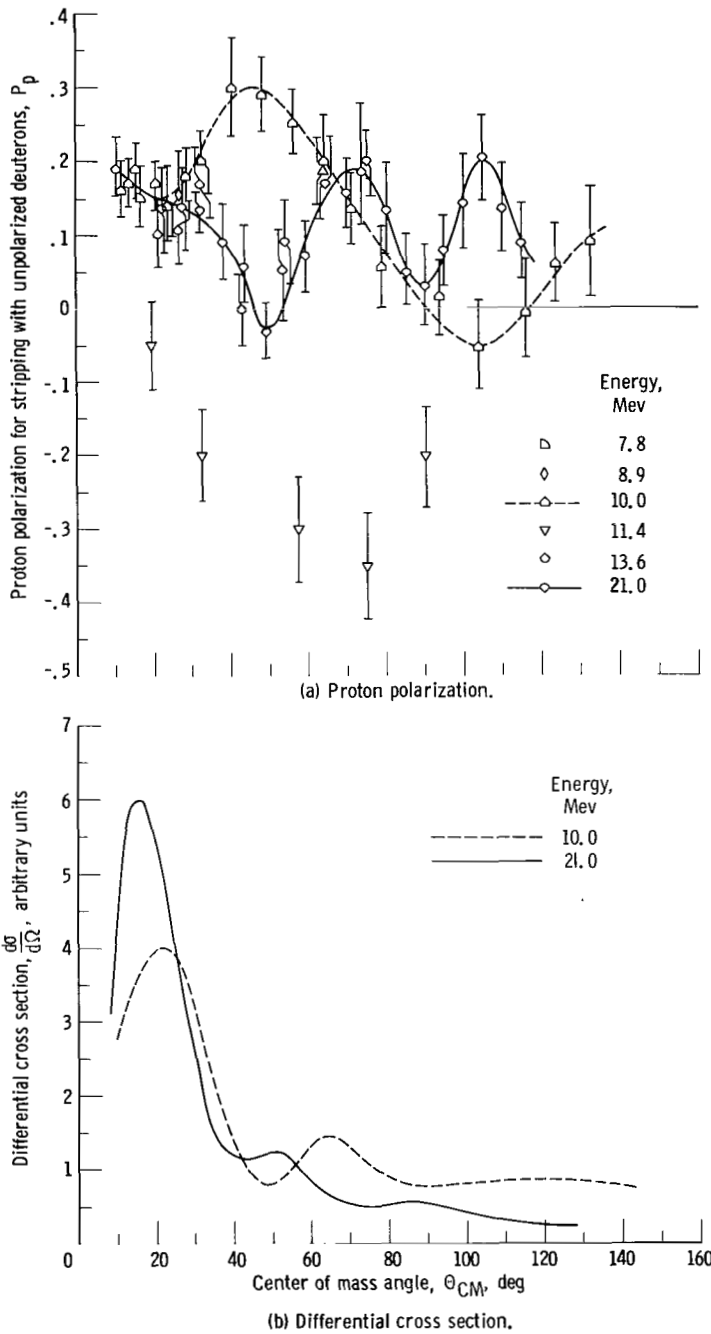


Figure 6. - Proton polarization and differential cross section from $B^{10}(d,p)B^{11}$ ground state reaction; transition, $3^+ \rightarrow \frac{3}{2}^-$; orbital angular momentum of captured neutron, 1; total angular momentum of captured neutron, $\frac{3}{2}$; reaction energy, 9.24 Mev. Angular distribution of cross section is taken from references 10 and 25.

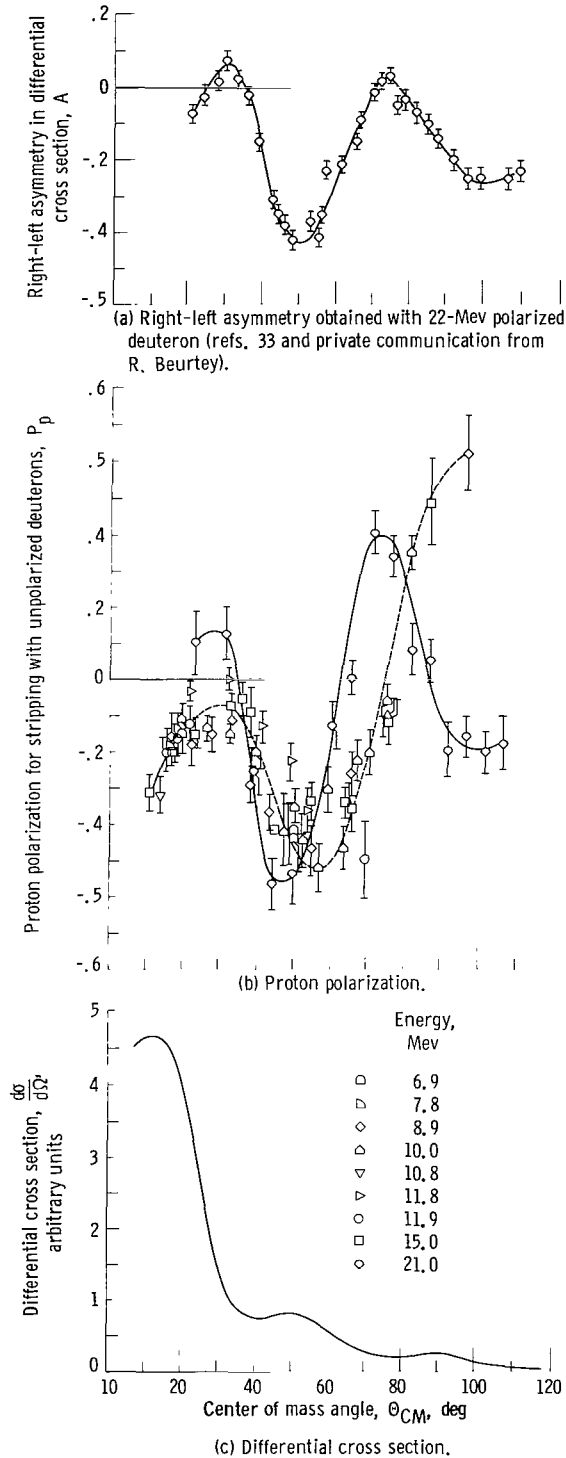


Figure 7. - Comparison of asymmetry, polarization, and differential cross section from $C^{12}(d,p)C^{13}$ ground state reaction; transition, $0^+ \rightarrow \frac{1}{2}$; orbital angular momentum of captured neutron, 1; total angular momentum of captured neutron, $\frac{1}{2}$; reaction energy, 2.72 Mev.

by the dashed line (see fig 7(b)). This also includes $C^{12}(d,n)N^{13}$ polarization at 11.8 Mev²⁶. The solid line in figure 7(b) connects the data points obtained for $E_d = 21$ Mev. The main feature at this energy is the substantial shift of the polarization distribution toward smaller angles and the positive sign of the polarization between 20° and 30° . Since the magnitude is larger than one-third, spin-dependent interactions are involved.

A detailed DWBA analysis for the $C^{12}(d,p)C^{13}$ reaction at $E_d = 8.9$ Mev has been made by Robson (ref. 32). In this work, he investigated the effects of radial cut-off and spin-orbit potentials in the DWBA on cross section and polarization. His analysis indicated that the contributions from the nuclear interior are significant and lead to a better fit of the cross section data. Even so, the calculated polarization did not resemble the experimental distribution. Subsequent inclusion of spin-orbit potentials in both the incident and final channel, however, reproduced the general trend of the experimental data both in magnitude and shape.

In the current stripping theory, a comparison between the cross section asymmetry induced by incident polarized deuterons and the proton polarization from stripping of unpolarized deuterons is useful for the investigation of spin-dependent forces and tensor interactions of the deuteron. Neglecting spin-orbit effects, Satchler (ref. 6) has derived the relation

$$\sigma(\theta)_{\text{pol}} = \sigma(\theta)_{\text{unpol}} (1 + 3\vec{P}_p \cdot \vec{P}_d) \quad (9)$$

where $\sigma(\theta)_{\text{pol}}$ and $\sigma(\theta)_{\text{unpol}}$ are the differential cross sections measured with polarized and unpolarized deu-

terons, respectively. This leads immediately to the expression $A = 3P_p P_d$.

The Saclay asymmetry measurements (ref. 33) for the $C^{12}(d,p)C^{13}$ g.s. reaction with 22-Mev approximately 50 percent vector-polarized deuterons are shown as the uppermost curve of figure 7. To determine the relation between

the right-left asymmetry of the cross section and proton polarization, pairs of experimental values of A and P_p for equal angles have been plotted in figure 8. Within the error bars, the resulting points can be located on the straight line

$$A = 0.47 P_p - 0.15 \quad (10)$$

The substantial disagreement of this experimental relation with Satchler's equation (eq. (3)) indicates the existence of spin-dependent effects, most probably arising from the spin-orbit force.

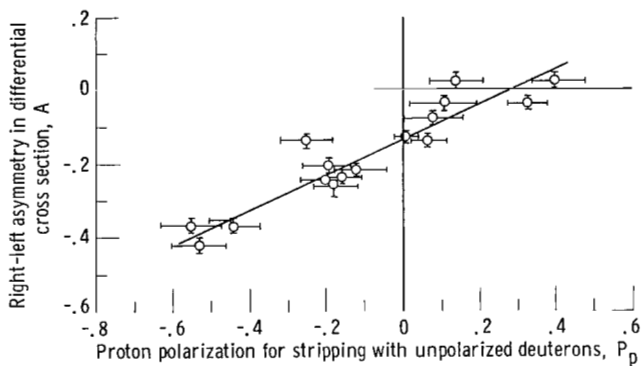


Figure 8. - Pairs of asymmetry and polarization data at equal angles taken from figure 7 are replotted.

The effect of spin-orbit forces on the polarization-asymmetry relation has been investigated by Robson (refs. 34 and 35). His expression is

$$\sigma(\theta)_{\text{pol}} = \sigma(\theta)_{\text{unpol}} (1 + f \vec{P}_p \cdot \vec{P}_d + \text{higher rank terms}) \quad (11)$$

where P_p and P_d are the aforementioned quantities and the factor f generally is a function of the angle but can simplify to a constant under certain circumstances. For the $C^{12}(d,p)C^{13}$ reaction, this is not the case, and a detailed analysis is required to understand the relation between A and P_p .

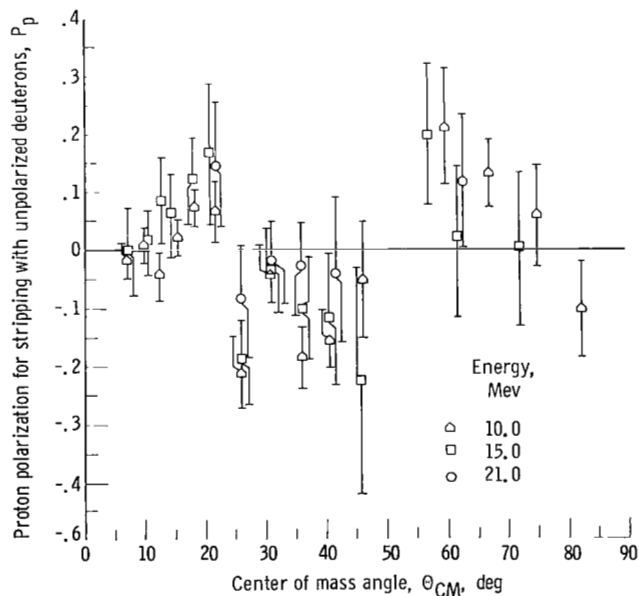


Figure 9. - Proton polarization from $Si^{28}(d,p)Si^{29}$ ground state reaction. Orbital angular momentum of captured neutron, 0; reaction energy, 6.25 Mev.

$Si^{28}(d,p)Si^{29}$ (ground state, $l_n = 0$)

The polarization of this reaction was measured as a case where the angular momentum of the captured neutron is zero. Such transitions are particularly interesting because the DWBA theory predicts zero polarization when spin-dependent interactions are ignored. At 10 and 15 Mev (refs. 23 and 30), this reaction has been studied, and a maximum polarization of 20 percent was found.

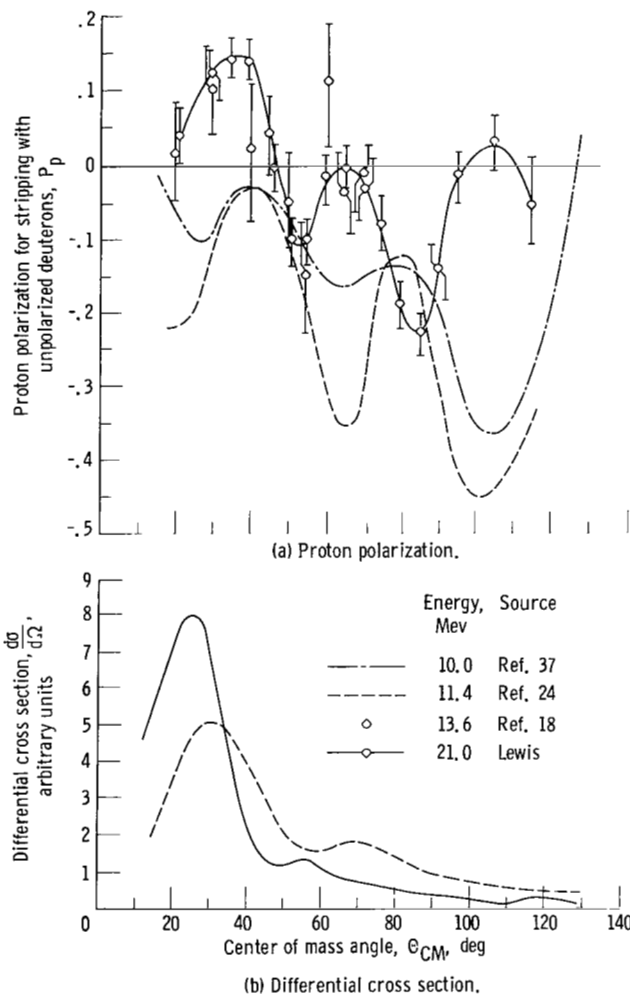
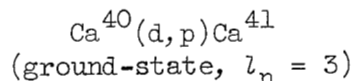


Figure 10. - Proton polarization and differential cross section from $\text{Ca}^{40}(\text{d}, \text{p})\text{Ca}^{41}$ ground state reaction; transition, $0^+ \rightarrow \frac{7}{2}^+$; orbital angular momentum of captured neutron, 3; total angular momentum of captured neutron, $\frac{7}{2}$; reaction energy, 6.14 Mev.

The angular dependence is very similar at both energies. We wanted to see if the similarities would persist at the deuteron energy of 21 Mev. Because of the difficulties in resolving the g.s. from the 1.28-Mev state in Si^{29} , the polarization was measured at only six angles. The data are presented in figure 9 along with the results at 10 and 15 Mev. In spite of the large statistical uncertainties, the data points suggest that the polarization distribution remains constant between 10 and 21 Mev; that is, the effects of the spin-orbit forces in Si^{28} are fairly independent of energy. A DWBA analysis of this reaction has been done at 10 and 15 Mev deuteron energy. The fits obtained are very satisfactory (private communication from W. R. Smith and ref. 36).



In figure 10, the polarization results at 21 Mev are compared with data at 10, 11.4, and 13.6 Mev (refs. 24, 18, and 37). The polarizations at 13.6 and 21 Mev are almost the same at forward angles, as were the polarization distributions for B^{10} at the same energy. At 10 and 11.4

Mev, there occurs a rapid change with energy, but the oscillatory pattern remains similar to the 21-Mev polarization. Most recently this reaction has been studied at 15 Mev (ref. 38). Up to 50° (laboratory angle) the results are similar to those at 10 Mev, and for larger angles the polarization curve lies between the 10- and 21-Mev distributions. Since $j_n = l_n + 1/2$ for this reaction, the sign rule for predominant deuteron distortion would imply positive polarization at the stripping peak. This agrees with the data at 13.6, 15, and 21 Mev. The disagreement at the two lower energies might be connected with the rapid fluctuation with energy that indicates interference from other reaction mechanisms. The differential cross section over the angular range of the polarization has been measured since no cross section data were available at this energy. The deuteron elastic cross section has been measured at 21 Mev (private communication from J. Yntema), the elastic deuteron polariza-

tion at 22 Mev (private communication from R. Beurtey), and the proton elastic polarization very recently at Lewis between 17 and 21 Mev (ref. 39). It is hoped that this rather complete experimental set will facilitate a theoretical understanding of this reaction.

CONCLUDING REMARKS

The following common features can be stated from the results of the reactions investigated:

1. The predictions of the central potential DWBA (eqs. (1) to (3)) are violated. The magnitude of the polarization is always at least slightly larger than the theoretical limit; the $\text{Si}^{28}(\text{d}, \text{p})$ polarization is nonzero and the relation between A and P_p in the Cl^{35} reaction cannot be described by equation (3). It is concluded that spin-dependent interactions are probably significant in all reactions.

2. The "sign rule" $P \gtrless 0$ for $j_n = l_n \pm 1/2$, is the one most often obeyed indicating that in these reactions the deuteron distortion outweighs the proton distortion. Even in the presence of spin-orbit effects, this sign rule should be valid in the stripping peak as was pointed out by Butler (ref. 40). Disagreement with the sign rule in B^{10} and Ca^{40} at 10 and 11.4 Mev could be related to the strong energy dependence of the (d, p) polarization in this energy region.

3. The energy dependence of polarization in deuteron stripping indicates that there are regions several Mev wide where the polarization changes very little. In Be^9 , B^{10} , and Ca^{40} between 10 and 12 Mev and in Cl^{35} between 15 and 21 Mev, rapid variations are observed whose nature cannot be explained at the present time.

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National Aeronautics and Space Administration
Cleveland, Ohio, September 18, 1964

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